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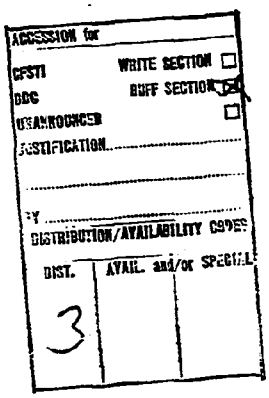
This document consists of 37 pages
(counting preliminary pages)
No 24 of 150 copies, Series A

(10) Charles E. Adams, Francis R. Holden
Norman R. Wallace.

(6) Scientific Director's Report of Atomic Weapons Tests at Eniwetok, 1951.

(11) Aug 51,
(12) 32 p.
(18) AEC
(19) WT-4

Annex 6.4
Fall-out Phenomenology,



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FALL-OUT PHENOMENOLOGY

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San Francisco 24, California
August 1951

Acknowledgments

The authors wish to thank A. R. Worley, LT, USN, for his competent and thorough field work under difficult conditions, and J. W. Washkuhn, J. P. Wittman, and J. V. Zaccor for their careful and patient laboratory examination of the fall-out samples.

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Abstract

An experiment was designed to measure the fall-out pattern and to study the nature of the fall-out particles from low-level, experimental atomic bomb air bursts in order to provide data for the appraisal of the potential health hazard from external and internal exposure to the fall-out products.

Samples of the fall-out from Dog and Easy Shots were obtained. A study of the size distribution of the active particles was made by size fractionation and radioautographic techniques. Radiochemical analyses of the fall-out were made. In addition, a study of the structure and composition of the fall-out particles was made.

It was determined that the bulk of the radioactivity in the fall-out was associated with particles greater than 5* in diameter. The highest radiation levels were found on Bogallua at E+30 min. The reading was about 30 r/hr as measured from a helicopter hovering 10 to 20 ft above the island.

* microns

Chapter 1

Introduction

1.1 OBJECTIVE

The objective of the 6.4 Fall-out Project was to collect samples of the primary and secondary fall-out from the Greenhouse atomic bomb detonations with the view of determining the level of activity and pattern of the fall-out, and of obtaining data on the size distribution and chemical nature of the active fall-out particles. This information was required for predicting fall-out patterns and probable external and internal hazards to personnel from fall-out particles from other atomic bomb air bursts.

1.2 HISTORICAL DATA

During previous atom bomb tests some data have been collected concerning fall-out. After the Alamogordo test a fall-out with high concentrations of radioactivity occurred several miles from the site of the explosion.[1]

During the Sandstone tests a secondary fall-out was reported from Kwajalein on Yoke plus one day.[2] The fall-out occurred as radioactive rain that fell intermittently during 10 hr. The maximum activity reported was 6 mr/hr on exposed cloth and tent sides, and 10 mr/hr in dried puddles. In this instance, the fall-out occurred about 36 hr after the explosion and at a distance of about 400 miles from the test site.

[1] *The Effects of Atomic Weapons* (Washington: U. S. Government Printing Office, 1950), p. 271.

[2] *Operation Sandstone*, Annex 9, "Kwajalein Fall-out".

Chapter 2

Experimental Procedure

2.1 DESCRIPTION OF APPARATUS

In view of the objective of the experiment and of the physical conditions at the site, it was necessary to design a fall-out collector according to the following requirements:

(1) To collect and hold as much of the fall-out dust as possible with due regard to wind and rain.

(2) To be light and relatively small in order that many collectors may be transported in a small boat and landed and emplaced on islands of the Atoll.

(3) To be simple in operation so that it may be set up easily and the fall-out samples quickly recovered.

(4) To be simply constructed so that large numbers may be manufactured inexpensively.

A fall-out collector has been designed to meet these requirements.[1] It consists of a 1-ft-square aluminum plate which is held in a horizontal position by a plate holder. The plate is covered with a thin layer of grease (Lubriseal) to entrap the particles that fall upon it. The greased plate is placed in the plate holder, which consists of a square box-like frame (see Fig. 2.1). The plate holder has sides which project 3 in. above the plate to provide protection from crosswinds. The collector is made watertight by fastening the plate in the plate holder with caulking compound. The collector is designed to prevent rain from washing away fall-out samples that are collected and to hold samples that fall as a radioactive rain. The plates are easily removed and replaced by freshly greased ones.

[1] Designed by Evan C. Evans III, USNRDL.

2.2 FIELD PROCEDURE

A few days prior to the first shot, ten plate holders were placed on each of the following islands: Bogallua, Kirinian, Piiraai, Aniyaanii, Parry, Eniwetok, Igurin, Giriinien, and Rigili. The holders were placed in five groups of two holders each in different locations on each island. Whenever possible the collectors were placed so that they were shielded by low vegetation from the prevailing surface winds but had an unobstructed exposure to the sky.

On D—1 day freshly greased fall-out plates were placed in all the holders.

On D-day, a few hours after the shot, each island was visited and the activity of the plates checked. The plates were removed from those islands which had received fall-out, and freshly greased plates left in their places.

From D+1 through D+6 days the activity of the plates on Bogallua, Parry, and Eniwetok was checked daily for indications of secondary fall-out.

All the active plates were returned to Eniwetok and there packaged and flown to U. S. Naval Radiological Defense Laboratory (USNRDL).

Owing to the small number of workers available for the project, it was found necessary to speed up the field procedure for the subsequent shots. To accomplish this, all the

collectors on each island were moved to a central point readily accessible from the airplane landing area. Also, as the rains had practically ceased, the use of caulking compound in sealing the plates in the holders was discontinued.

Other than these changes the procedure for Easy and George Shots was the same as for Dog Shot.

Throughout the tests, helicopters and light airplanes were used for transportation to all islands except Parry and Eniwetok.

Chapter 3

Test Results

3.1 DESCRIPTION OF FALL-OUT ON ENIWETOK ATOLL

Following Dog Shot, a fall-out occurred over the southern half of the Atoll. The fall-out on Eniwetok Island started approximately 3 hr after the shot and continued to build up for a few hours. By the middle of the afternoon it had reached its peak and the activity began to decrease. No secondary fall-out was observed through D+6 days.

Within a few hours following Easy Shot, a fall-out occurred which was restricted to the northern islands in the vicinity of the shot island. A small secondary fall-out occurred on E+1 day which was only observed on Aniyaanii, Parry, and Eniwetok.

No fall-out was observed on the Atoll following George Shot.

The radioactivities measured on the fall-out plates of the nine islands following Dog and Easy Shots are tabulated in Table 3.1. All measurements were made with either a Victoreen model 263B beta-gamma survey meter

TABLE 3.1 RADIOACTIVE FALL-OUT FOLLOWING DOG AND EASY SHOTS

ISLAND	DOG SHOT			EASY SHOT		
	Date	Time	Radioactivity, mr/hr (Gamma)	Date	Time	Radioactivity, mr/hr (Gamma)
Bogallua	D-day	1500	0.3	E-day	0700	30,000[a]
				E+1	1330	1,500
Kirinian	D-day	1530	0.2	E-day	1400	225
				E+1	1415	65–80
Piiraai	D-day	1600	0.2	E-day	1340	120
				E+1	1440	19
Aniyaanii	D-day	1700	38– 48	E-day	1000	0.5[b]
				E+1	1450	2.0
Parry	D-day	1410	100	E-day	1530	0.4–0.6[b]
	D+1	1420	18	E+1	1430	11–20[b]
Eniwetok	D-day	1700	30– 43	E-day	1130	0.4–0.6[b]
				E+1	1100	3–11[b]
Igurin	D-day	1100	110–140	E-day	1150	0.7[b]
	D+1	1630	22			
Giriinien	D-day	1120	220[a]	E-day	1140	4
	D+1	1550	80–140			
Rigili	D-day	1140	250[a]	E-day	1120	5
	D+1	1500	95–140			

[a] Reading made by a radiological safety officer in a helicopter approximately 10 to 20 ft above the island.

[b] Beta plus gamma activity.

with the window closed or with an AN/PDR-T1B gamma survey meter. Unless otherwise noted, the measurements were made with the instrument 0.5 to 1 in. above the fall-out plate.

3.2 LABORATORY EXAMINATION OF FALL-OUT

3.2.1 Size Fractionation by Sedimentation Methods

In order to determine the size range of the active particles, a method was devised for separating the fall-out samples into three size fractions. By means of this method the sample may be divided into a fine fraction containing particles with diameters of less than 2 μ, a medium fraction 2 to 20 μ in diameter, and a large fraction greater than 20 μ in diameter.

The fall-out particles were removed from the plate by washing with xylene until the radioactivity of the plate was down to normal background. The xylene suspension was poured into a beaker to a depth of about 2.5 in. The suspension was stirred and then allowed to settle for 2 min. The supernatant liquid containing most of the small particles was decanted, leaving the sediment containing large particles mixed with small particles in the bottom of the beaker. Fresh xylene was added to the beaker and the sediment redispersed by stirring. The suspension was allowed to settle 2 min and then decanted as before. This process was performed a total of ten times. By this time practically all the particles less than 20 μ in diameter had been removed from the sediment. This sediment constituted the large fraction.

The supernatant liquid containing the particles less than 20 μ in diameter was centrifuged for 0.5 hr at a speed sufficient to precipitate all particles larger than 0.25 μ in diameter. The supernatant xylene was decanted and saved. Fresh xylene was added to the precipitate in order to dissolve remaining traces of Lubriseal. The suspension was again centrifuged and decanted. The xylene was removed from the particles with two washes of dioxane. The particles were then dispersed in water to which a small amount of dispersing agent had been added. During the centrifugations the particles had become badly agglomerated. In order to break up the agglomerates the suspension was agitated by means of ultrasonic vibrations (400 kc) for a few minutes. The sample was then separated into two sizes of fractions by the following method.

A hole approximately 0.25 in. in diameter was blown through the bottom of a 15-ml centrifuge tube. This tube was fitted into a 50-ml conical centrifuge tube by means of a rubber stopper so that in effect a double-layered centrifuge tube was made. Thirty ml of a solution of urea in water (800 g of urea in 1,000 ml of water) was added to the two tubes.[1] Approximately 1 ml of the aqueous suspension of particles was carefully floated in the inner 15-ml tube on top of the urea solution (see Fig. 3.1). Empirically, it was found that after centrifuging the tubes for 2.25 min at 1,100 rpm the top layer in the inner tube contained very few particles greater than 2 μ in diameter, while the sediment in the bottom of the 50-ml tube contained very few particles less than 2 μ in diameter. The liquid in the central portion of the 15-ml tube contained particles of all sizes.

The top layer from the inner tube containing the fine fraction was removed with a medicine dropper. A rubber stopper with an open air vent was then inserted into the inner tube, the air vent closed, and the tube withdrawn from the 50-ml tube. The contents of the inner tube containing the particles of mixed sizes were emptied by opening the air vent in the rubber stopper. This portion of the suspension was saved for recycling. The medium fraction containing particles 2 to 20 μ in diameter remained in the bottom of the 50-ml tube, from which it was withdrawn with a medicine dropper.

[1] The use of urea for this purpose was suggested by C. E. Marshall, "A New Method of Determining the Distribution Curve of Polydisperse Colloidal Systems," *Proc. Roy. Soc.*, CXXVI, Series A, No. A802 (1930), 427.

This process was repeated until the entire sample had been divided into the two size fractions and a third portion containing particles of all sizes. This portion was centrifuged to concentrate the particles, the supernatant liquid was decanted, and the sediment was redispersed in a smaller amount of water. The sample was then fractionated by the above procedure, and the fine and medium fractions were added to the previously obtained fractions.

The medium fraction was further purified by redispersing the sediment in about 30 ml of water and centrifuging the suspension for 2.25 min in a 50-ml centrifuge tube. The supernatant liquid was decanted and discarded. The sediment was again dispersed in water and centrifuged and the supernate discarded. This process was performed three times. By this time practically all particles less than 2 μ in diameter had been removed in the decanted liquid.

The fine fraction was purified by dispersing in 30 ml of water, centrifuging for 2.25 min in a 50-ml tube, and decanting the supernatant liquid. The sediment in the bottom of the tube was redispersed in 30 ml of water and again centrifuged for 2.25 min. The supernatant liquid was decanted and added to that previously decanted. This liquid contained the fine fraction with very few particles greater than 2 μ in diameter.

Each size fraction was then placed on previously dried and weighed rectangular microcover glasses. Any fraction containing a large amount of material was subdivided onto two or more cover glasses. The fractions were then oven-dried, weighed, and counted.

Samples from each of the islands that received fall-out were analyzed by this method. The results are tabulated in Table 3.2.

The amount of activity lost in the xylene washes was determined by concentrating the supernatant liquid saved from the centrifugations by prolonged gentle heating and then counting the residue. About 1 to 8 per cent of the total activity of the samples was found to be in the residue. To determine whether this activity was in solution or on small particles suspended in the xylene, three small samples of the active xylene were centrifuged at high speed for a time sufficient to precipitate all particles greater than 0.02 μ in diameter (assuming a particle density of 3.0). The supernatant liquid was withdrawn from the tube, evaporated, and counted. A small amount of fresh xylene was added to the sediment remaining in the tube. The sediment was redispersed in the xylene by use of the ultrasonerator. The suspension was withdrawn, evaporated, and counted. By comparison of the two counts, it was found that 93 to 99 per cent of the activity remained in the supernatant liquid and was probably in solution in the xylene.

3.2.2 Microscopic Examination of Fall-out Particles

By adapting a method of radioautography developed for the identification and measurement of radioactive particles in Project 6.1,[2] it was possible to examine with the microscope individual active fall-out particles. The particles were removed from the fall-out plate by flowing liquid plastic[3] over an area of 2 or 3 sq in. and then letting the plastic harden for a few hours. After hardening, the film was easily stripped from the aluminum plate. It was found that the particles were well embedded in the plastic, leaving the plate surface quite clean.

The plastic film was cut into small pieces and each piece was cemented to a rectangular microscope cover glass with a gelatin-alum mixture. The side of the film not containing the particles was placed next to the cover glass. A small piece of Eastman NTB stripping film was cemented over the plastic film with the emulsion side of the film out. The samples were exposed for a few days, the

[2] Refer to microradioautographic technique described in Greenhouse Report, Annex 6.1.

[3] A plastic with a synthetic resin base manufactured by the Minnesota Mining and Manufacturing Co. (No. EC-968) was used. The plastic was diluted with methyl isobutyl ketone to a thin flowable consistency.

length of time being roughly proportional to the activity on each slide. After development, the slides were examined and a number of exposed spots on the film were found. By using above-stage lighting, it was possible to identify a radioactive particle in or near the center of most of the spots.

The advantage of this method is that it enables the study of the active particles in an undisturbed state as they fell onto the fall-out plates. There is no danger of disrupting their structure or breaking down agglomerates as there is in the sedimentation procedure. The disadvantage of the method is that it is not applicable to particles less than 0.5 μ due to the limitation of the optical microscope and to the relatively low level of activity of small particles necessitating a very long exposure during which the film is blackened excessively by the larger, more highly radioactive particles.

A microscopic study of these slides showed that the radioautographs were almost exclusively associated with black spheres. These black spheres ranged in size from about 450 μ in diameter to submicroscopic dimensions.

The spheres showed three modes of occurrence: (1) as individual particles, (2) as parti-

TABLE 3.2 RELATIVE RADIOACTIVITIES OF FALL-OUT SIZE FRACTIONS

SHOT	ISLAND	SIZE OF FRACTION (μ)	WEIGHT OF FRACTION (mg)	TOTAL COUNTS[a] PER MIN PER PLATE $\times 10^{-5}$	PER CENT OF TOTAL ACTIVITY
Dog	Aniyaanii	<2	0.4	0.35[b]	0.5
		2–20	2.3	2.4	4
		>20	142.2	57.0	95.5
Dog	Parry	<2	4.8	1.40[c]	3
		2–20	6.3	6.0	14
		>20	113.3	36.5	83
Dog	Eniwetok	<2	1.1	4.4[b]	12
		2–20	4.8	4.2	12
		>20	1,809.8	27.3	76
Dog	Igurin	<2	1.0	0.87[b]	2
		2–20	3.9	6.1	13
		>20	1,952.9	40.2	85
Dog	Giriinien	<2	0.6	15.9[b]	6.5
		2–20	2.0	15.9	6.5
		>20	1,133.9	214.0	87
Dog	Rigili	<2	0.7	59.1[b]	8
		2–20	3.8	96.9	14
		>20	39.9	549.5	78
Easy	Bogallua	<2	1.6	152[b]	1
		2–20	17.6	1,510	7
		>20	160.4	19,300	92
Easy	Kirinian	<2	2.7	17.8[b]	1
		2–20	2.5	76.2	6
		>20	44.2	1,380	93
Easy	Piiraai	<2	0.9	6.8[d]	0.5
		2–20	5.6	41.5	3.5
		>20	49.5	1,156	96

[a] The total counts per minute have been corrected for decay back to shot time plus 10 hr by means of the decay curves for Dog and Easy Shots obtained from Project 6.1.

[b] Geometry of counter is 3 per cent as determined by use of a RaDE standard.

[c] Geometry of counter is 2 per cent (RaDE standard).

[d] Geometry of counter is 8 per cent (RaDE standard).

cles adhering to coral grains, and (3) in loosely associated clusters of spheres and granules of a transparent material.

Approximately one-third of the radioactive particles found on the slides were individual spheres. These spheres were almost perfectly round and superficially homogeneous. They ranged from about 1 to 20 μ in diameter. They were found in all samples from both Dog and Easy Shots. Figures 3.2 and 3.3 show the size distribution of a number of spheres measured in samples collected on Rigili and Bogallua Islands. Many of the Easy Shot samples showed that a high percentage of the activity was due to individual spheres or subspherical particles 200 to 450 μ in diameter. These spheres exhibited a granular texture under the microscope. Their surfaces were irregular and had a black, glossy, beaded appearance. Very small grains of what appeared to be calcium carbonate were adhering to the surfaces. (The grains had very high birefringence, characteristic of calcium carbonate, under the petrographic microscope.) Some of the spheres had cracks and cavities, the appearance of which suggested that the granular structure persisted throughout the interior of the sphere. A number of these large spheres were removed from a fall-out plate with tweezers, and their diameters and radioactivity measured. There was no relationship between the sizes of the particles and their activities. One sphere was found that counted approximately 3×10^6 disintegrations/sec (corrected to E+10 hr).

Most of the black spheres, especially in the Dog Shot samples, were found adhering to coral grains. The sizes of the black spheres so found varied from about 10 μ in diameter to submicroscopic. The number of adhering spheres per grain varied from 2 or 3 to perhaps 50. The sizes of the coral grains themselves varied from about 10 to 500 μ in diameter. A large number of these radioactive grains from the Rigili and Bogallua samples were measured, and their size distribution is shown in Figs. 3.4 and 3.5. Where these grains were thin enough to be viewed with transmitted light in the petrographic microscope they exhibited the characteristic very high birefringence of calcium carbonate. There were a large number of salt crystals visible in the slides, none of which were observed to carry radioactive particles. In one instance, a vegetable fiber was found which had a large number of radioactive spheres on the order of 1 or 2 μ in diameter adhering to it. Only a very small fraction of the total number of particles found on the slides carried radioactive particles.

In quite a few cases the active spheres were found in very loose, irregular aggregates or clusters intimately mixed with an amber-colored, isotropic, glassy material. Parts of the aggregate were separated from each other. Apparently the particles fell as loosely bound floccules which shattered when they hit the fall-out plate.

All the data on the measurements of radioactive particles by the radioautographic technique have been compiled in Appendix A, Table A.1.

3.2.3 Chemical Analysis of Fall-out Samples

Six samples of the Easy Shot fall-out from Bogallua were analyzed for the radioactive elements present. The six samples were:

(1) An unfractionated sample removed directly from the fall-out plate with xylene and concentrated by centrifugation.

(2) The xylene supernate from this centrifugation.

(3) A sample of the large radioactive spheres picked with tweezers from a fall-out plate.

(4) The small fraction from a sample which had been size-fractionated by the sedimentation method.

(5) The medium-size fraction.

(6) The large-size fraction.

The results of the analyses are shown in Table 3.3.

Several of the large spheres, 200 to 450 μ in diameter, were analyzed spectrographically to determine the elements which make up the bulk of the particles (see Table 3.4).

In addition, an attempt was made to identify the composition of the large spheres by X-ray diffraction. A powder photograph showed a series of lines which indicated the composition of the particles to be about one-third calcium carbonate (calcite), one-third calcium oxide, and one-third unidentified compounds.

3.2.4 Radioautographs of Fall-out Plates

Radioautographs of many of the fall-out plates were made shortly after their arrival at USNRDL. A typical one is reproduced in Fig. 3.6. This radioautograph was made from a fall-out plate from Parry Island (Dog Shot) with Eastman Type K X-ray film enclosed in two lighttight envelopes. The packaged film was pressed against the fall-out plate with sponge rubber, plywood, and a lead brick, and was exposed for 5 hr on D+7 days.

By means of another series of exposures, the radioactivities associated with two of the spots were determined with a densitometer designed for small areas. The activities of spots A and B (Fig. 3.6) were found to be 14 and 24 rep/hr, respectively (at the surface of the fall-out plate), on D+9 days.

TABLE 3.3 RADIOCHEMICAL ANALYSES OF EASY SHOT FALL-OUT

ELEMENT	UNFRACTIONATED SAMPLE		XYLENE WASH		LARGE SPHERES 200–450 μ IN DIAM	
	Found (%)	Theoretical (%)*	Found (%)	Theoretical (%)	Found (%)	Theoretical (%)
Total rare earths—La, Pr, Nd, Ce, Y	63	60	79	58	60	62.5
Ba	5.6	11.8	6.3	8.9	6	21.5
Sr	0.7	10	....	....		
Zr	16.3	9	3.2	11.6	16.6	8
Ru	5.5	4	3.8	4.7	9.0	4
TOTAL	91	95	92	83	92	96
Time of Analysis	E+39 days		E+53 days		E+33 days	
	Small Fraction, Less than 2μ		Medium Fraction, 2 to 20μ		Large Fraction, Greater than 20μ	
Total rare earths	82	59	88	60	73	60
Ba	5	12	11.2	22	3.6	12.6
Sr	....	....			0.1	8.7
Zr	12	9	....	....	14.1	7.3
Ru	....	....	....	....	5.0	5.8
TOTAL	99	80	99	82	96	94
Time of Analysis	E+39 days		E+35 days		E+27 days	

* The calculated theoretical percentages are determined from considerations of the fission-yield report, USNRDL Report ADC–65, H. F. Hunter and N. E. Ballou, *Simultaneous Slow Neutron Fission of U^{235} Atoms*, and the recent Greenhouse data on fission yields.

TABLE 3.4 SPECTROCHEMICAL ANALYSIS OF LARGE FALL-OUT PARTICLES

ELEMENT	STRENGTH OF LINES	
Al	W	
Ca	VS	
Cu	W	
Fe	M	T=0.001–0.01%
Mg	T	W=0.01–0.1%
Mn	T	M=0.1–1%
Si	S	S=1–10%
Sn	T–W	VS=>10%
Ti	S	
Zn	T–W	

Chapter 4

Discussion

4.1 RELIABILITY OF EXPERIMENTAL PROCEDURE

The results of the sedimentation procedure indicate a moderate amount of radioactivity on particles in the small- and medium-size fractions from the Dog Shot samples. These results differ consistently from the results of the Easy Shot fall-out analysis which indicate that practically all of the radioactivity is associated with the large fraction.

As it might be expected from a consideration of the settling velocities of particles in air that the fall-out should consist of large particles only, the apparent high percentage of active small particles in the Dog Shot fall-out is surprising. The question arises whether the small particles actually fell to the ground individually or whether they fell attached to larger grains and were dislodged during the sedimentation procedure.

The removal of the particles from the fall-out plates and the separation of the large fractions from the small and medium fractions were done with the particles suspended in xylene. Xylene, being a hydrocarbon whose molecule contains no polar groups, does not tend to disperse particles suspended in it. It does not seem likely that a significant dispersion of the particles occurred in these stages.

During the process of separation of the medium from the small fractions, the samples were suspended in water and subjected to ultrasoneration. At this point it is probable that an appreciable dispersion of the particles occurred which would result in an increase in the number of radioactive small particles at the expense of the medium-size particles.

From these considerations considerable doubt is cast upon the accuracy of the fractionation in the smaller size ranges. That particles in the medium-size range actually fall out individually is, however, borne out by the results of the microscopic examination of the radioautographs in which single particles down to 1 μ in diameter were found.

Very few radioactive particles smaller than 2 μ were found by this method. This indicates that most of the radioactivity of the small fraction was due to the small radioactive spheres removed from the large coral grains during the sedimentation procedure.

4.2 ORIGIN OF THE FALL-OUT PARTICLES

It seems probable that the black, radioactive spheres originated by condensation of material from the ball of fire within a short time after the shot. The only evidence available as to the chemical composition of the particles comes from the spectrographic analysis of the large (200 to 450 μ) spheres from the Bogallua fall-out after Easy Shot. The major constituents are calcium, silicon, iron, and titanium. The calcium must have originated from the vaporization of large amounts of coral (almost exclusively calcium carbonate) near the base of the shot-tower. The iron and silicon probably came from the vaporization of the steel tower and its concrete foundation. A source of large amounts of titanium is unknown. The results of the X-ray diffraction study of these spheres show that the calcium is in the form of the carbonate and the oxide. It seems likely that the calcium originally condensed as the oxide and by reaction with carbon di-

oxide in the air has been partially converted to the carbonate. No evidence of calcium hydroxide was found. The carbonate shows the crystal structure of calcite in contrast to the unaltered coral sand which has the aragonite structure.

Examination of the radiochemical analysis of the fall-out shows that fractionation of the active elements has occurred during the formation of the particles. The relative amounts of strontium and barium are consistently less, in comparison with the other radioactive elements reported, than would be expected from the normal fission-yield distribution. An examination of the fission-product chains[1] shows that the strontium isotope most likely to be found in the radiochemical analysis has Kr^{89} with a 2.6-min half life for an ancestor. Most of the Kr^{89} formed in fission would not have decayed at the time of formation of the spherical particles. Similarly, barium has as an ancestor Xe^{140} with a 16-sec half life. From the half lives of their gaseous ancestors, it would be expected that there would be considerably less strontium in the fall-out particles than barium. This is actually the case. The amount of strontium reported varies from about 1 to 7 per cent of what would be expected from the normal yield, while the amount of barium present is about 50 per cent.

As previously described, most of the fall-out particles collected consist of inert coral grains with several small, radioactive spheres adhering. It does not seem likely that the spheres became attached to the sand grains after the spheres reached the surface of the ground. In that case it would be expected that the spheres would be more or less evenly distributed over all the surface grains, and that there would be a high percentage of free spheres in the fall-out collectors. Such is not the case. The number of active grains relative to the number of inactive grains is very small, as is the number of free spheres relative to the number of active grains. It seems probable that the spheres became attached to the grains in the air after the spheres had formed and the ball of fire had cooled to a relatively low temperature. The coral grains show no indication of having been fused, and in one case the spheres are found adhering to a vegetable fiber. Probably a considerable amount of surface debris was carried aloft by the strong updrafts following the ascent of the ball of fire. Many of the small spheres formed in the radioactive cloud must have adhered to this debris which subsequently reached the ground as fall-out.

[1] Plutonium Project, "Nuclei Formed in Fission," *J. Am. Chem. Soc.*, LXVIII (1946), 2411.

4.3 MECHANISM OF FALL-OUT

Stokes' law is of value in explaining the mechanism of, or predicting, fall-out. However, one of the basic assumptions of the law is streamline, nonturbulent settling, which condition certainly does not prevail in the vicinity of an atomic blast. Quite a number of individual radioactive particles 5 μ in diameter were found in the radioautographs of the fall-out. According to Stokes' law it should take a spherical 5-μ particle about 4 weeks to fall from 20,000 ft to sea level (assuming a particle density of 3.0). It is obvious that the downward velocity of the particles must be affected by some mechanism other than mere gravitational settling.

It is known that during the development of cumulus clouds, where strong updrafts rise rapidly to heights of many thousands of feet, there are associated weaker down currents of air somewhat after the manner of convection currents. These downdrafts occur around the central rising current and extend out to a distance of several times the diameter of the rising current. It seems possible that there could be some such development of down currents in the vicinity of the rising atomic cloud which could give to a swarm of particles a downward velocity *much greater than their normal settling velocities.* In such a case, the particles would be carried downward with a velocity independent of their size, and the resulting fall-out would show much less size segregation than if it were due to Stokes'-law-settling alone.

4.4 INFLUENCE OF LOCAL WINDS ON FALL-OUT

Data were obtained from the Air Force meteorology station on Eniwetok on the wind directions and velocities from sea level up to about 45,000 ft at the time of each shot and for a period of several hours thereafter. By proper plotting of these data it is possible to predict the localities at which fall-out would occur if the following assumptions are made: (1) the fall-out descends at a constant velocity, (2) there are no turbulences or up- or downdrafts, and (3) the fall-out material originates from a line source rising vertically over the shot point.

Using the Air Force meteorological data, a chart was made showing the probable fall-out path (Fig. 4.1). The plot was constructed as follows: Assuming no turbulence or updraft, a constant velocity of descent of 10,000 ft/hr was chosen as a first approximation. Assuming the fall-out starts at an elevation of 2,000 ft, and that the time of fall through 2,000 ft is 0.2 hr, the point at which it would reach the surface was plotted taking into consideration the average wind direction and velocity between the surface and 2,000 ft. Another point was plotted assuming the fall-out starts at an elevation of 4,000 ft and computing the average wind direction and velocity between 4,000 and 2,000 ft and between 2,000 ft and the surface. The change of wind direction and velocity with time was taken into account.[2]

In this manner a series of points was obtained which were connected by a curve. This curve represents the locus along which fall-out could occur in the case where the velocity of descent was 10,000 ft/hr.

By assuming different velocities of descent other curves were drawn. The result was a family of curves in which each curve represents a different velocity of descent and points along the curves represent different original elevations of the fall-out material. As wind direction normally varies with altitude, for any point on the chart there exists a unique velocity curve and a unique original elevation.[3] From these considerations, and within the limits of the original assumptions, it is possible to predict the probable path of the fall-out and also to determine the rate of fall and original elevation of the fall-out material reaching the surface at any point.

From an examination of Fig. 4.1, the data indicate for Dog Shot that the fall-out would be general over the southern half of the Atoll with no possibility of fall-out occurring on any of the islands north of Runit or Rigili. There does not seem to be any possibility of secondary fall-out. Presumably, secondary fall-out would come from very slowly falling material which would take a day or more to reach sea level. From the chart, it can be seen that as the velocity of descent decreases the fall-out path moves farther and farther south, so that any fall-out occurring later than D-day should have passed entirely south of the Atoll (assuming no great change in the wind pattern).

Referring to the fall-out data in Table 3.1, it is seen that the actual fall-out pattern is just what would be indicated from the chart. The fall-out was general over the southern half of the Atoll with the greatest concentration on Rigili. There was no fall-out detected on any of the islands north of Rigili and Runit. No secondary fall-out was observed.

It is interesting to note that according to the chart the fall-out on Eniwetok should have originated at 45,000 ft and descended at 10,000 ft/hr. According to these figures the fall-out should have reached Eniwetok about 4.5 hr after shot time. Actually, the fall-out was first noticed about 3 hr after shot time.

From an examination of Fig. 4.1 for Easy Shot it is indicated that the maximum fall-out should occur over the northernmost islands in the vicinity of the shot island (Engebi). If fall-out were to occur over the southern part of the Atoll it would descend slowly and not reach the surface until a day or so after the shot. From Table 3.1 it is seen that the in-

[2] *The Effects of Atomic Weapons* (Washington: U. S. Government Printing Office, 1950), p 438.

[3] For the case where the wind direction is constant at all altitudes there is no unique solution.

itial fall-out was confined to the northern islands with no fall-out occurring south of Bogallua and Piiraai. Also, a small secondary fall-out did occur on some of the islands in the southern part of the Atoll on E+1 day. The unusually heavy fall-out on Bogallua might be explained upon examining the fall-out curves, whereby it is seen that the vicinity of Bogallua could have received fall-out originating throughout a very wide range of elevations.

It is apparent from Fig. 4.1 that there was no possibility of any fall-out on the Atoll following George Shot.

It should be borne in mind, of course, that the path of the fall-out cannot be accurately indicated by a line but, due to atmospheric turbulence, would be more closely approximated by a long, narrow cone. Also, the fall-out material would not originate from a vertical line source above the shot point but would come from a column about 0.5 mile in diameter.

However, even with these limitations, the preceding method apparently furnishes a fairly reliable method of predicting fall-out.

Chapter 5

Conclusions

The fundamental purpose of Project 6.4 was to provide data for the determination of the health hazard to personnel resulting from radioactive fall-out from low-level atomic bomb bursts.

The fall-out during Operation Greenhouse was not heavy enough on any of the islands, with the exception of Bogallua, to cause a serious danger from external radiation. It was computed that a person exposed on Bogallua for 24 hr from the initial time of fall-out, taken as E+1 hr, would have received a total-body dose of 117 r of gamma radiation alone (calculated using an activity reading of 1.5 r/hr at E+31 hr and the decay curve for Easy Shot fission products from USNRDL Project 6.1 data). However, under circumstances where transportation from the contaminated area would be available, the hazard would not be important, although localized areas might be declared unsafe for a period of several hours or days.

The danger of internal radiation from fall-out lies in the retention in the body of radioactive particles inhaled or ingested. The retention in the lung is most pronounced for particles in the vicinity of 1 μ in diameter.[1]

Results of this investigation indicate that only a very small percentage of the radioactivity of the fall-out was associated with particles near this size. However, active particles of this size were encountered in the fall-out, and small quantities might have been inhaled or ingested by the personnel on the Atoll. Whether or not a few, small, radioactive particles lodged in the lung constitute a health hazard is not known.

To clear up ambiguities which have arisen as to how many of the small, active particles fell out individually or adhered to larger particles, it is recommended that in future fall-out studies, aerosol-collecting instruments such as electrostatic or thermal precipitators be used at ground levels with the precipitation of particles upon microscope cover glasses in order that the radioautographic technique may be used to identify and measure the active particles.

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[1] J. H. Brown, K. M. Look, F. G. Ney, and T. Hatch, "Influence of Particle Size upon the Retention of Particulate Matter in the Human Lung," *Am. J. of Public Health*, XL, No. 4 (1950), 450.

Appendix A

Size Distribution of Radioactive Fall-out Particles

Table A.1 is a compilation of measurements of all the radioactive particles found with the radioautographic technique described in Section 3.2.2. The figures in the table are the numbers of particles whose diameters fall within a given size range.

Figures 3.2, 3.3, 3.4, and 3.5 were drawn using data from this table.

TABLE A.1 SIZE DISTRIBUTION OF RADIOACTIVE FALL-OUT PARTICLES

DIAMETER (μ)	EASY SHOT				DOG SHOT									
	Bogallua		Kirinian		Aniyaanii		Parry		Eniwetok		Igurin		Rigili	
	Individual Spheres	Active Coral Grains	Individual Spheres	Active Coral Grains	Individual Spheres	Active Coral Grains	Individual Spheres	Active Coral Grains	Individual Spheres	Active Coral Grains	Individual Spheres	Active Coral Grains	Individual Spheres	Active Coral Grains
0.0 – 1.0	1	..	..	..	..	..	..	..	..	..	..	..	..	..
1.0 – 1.25	2	..	..	..	..	..	..	..	..	..	..	..	..	..
1.25– 1.6	3	..	1	..	..	..	..	..	..	..	..	..	5	..
1.6 – 2.0	12	..	1	..	1	..	..	..	..	..	1	..	8	..
2.0 – 2.5	11	..	2	..	1	..	..	..	..	..	1	..	10	..
2.5 – 3.2	18	2	..	1	1	..	1	..	..	..	3	..	21	..
3.2 – 4.0	40	4	5	..	2	..	1	..	3	..	2	1	22	1
4.0 – 5.0	40	11	1	2	4	3	1	..	2	..	4	..	27	3
5.0 – 6.3	59	23	7	2	2	..	1	1	3	..	1	..	23	5
6.3 – 8.0	53	36	9	5	1	..	1	..	2	1	1	1	11	14
8.0 – 10.0	28	43	1	3	3	4	..	1	..	2	1	2	8	9
10.0 – 12.5	18	52	1	6	..	4	..	1	1	..	2	4	2	10
12.5 – 16.0	19	60	..	5	1	1	..	1	..	..	1	1	..	23
16.0 – 20.0	6	60	..	10	..	1	..	1	1	2	..	1	..	15
20 – 25	1	65	..	7	..	1	..	..	..	2	..	..	1	19
25 – 32	1	59	..	3	1	..	..	3	..	2	..	..	..	21
32 – 40	3	37	..	5	..	1	..	..	..	2	..	1	1	16
40 – 50	..	33	..	5	..	..	..	..	..	3	..	1	..	11
50 – 63	1	30	..	5	..	..	..	2	..	4	..	..	..	4
63 – 80	..	18	..	4	..	1	..	2	..	2	..	..	1	10
80 – 100	..	15	..	5	..	..	..	3	..	3	..	..	..	4
100 – 200	..	29	..	19	..	4	..	9	..	7	..	1	..	13
200 – 500	..	12	..	5	..	4	..	2	..	6	..	4	..	4
500 –1000	..	8	..	..	..	..	..	..	..	..	..	..	..	..
TOTAL	316	597	28	92	17	24	5	26	12	36	17	17	140	182

Appendix B

Personnel Logistics

B.1 ROSTER OF PERSONNEL

The following men were responsible for setting out, monitoring, and picking up the fallout collectors at the site:

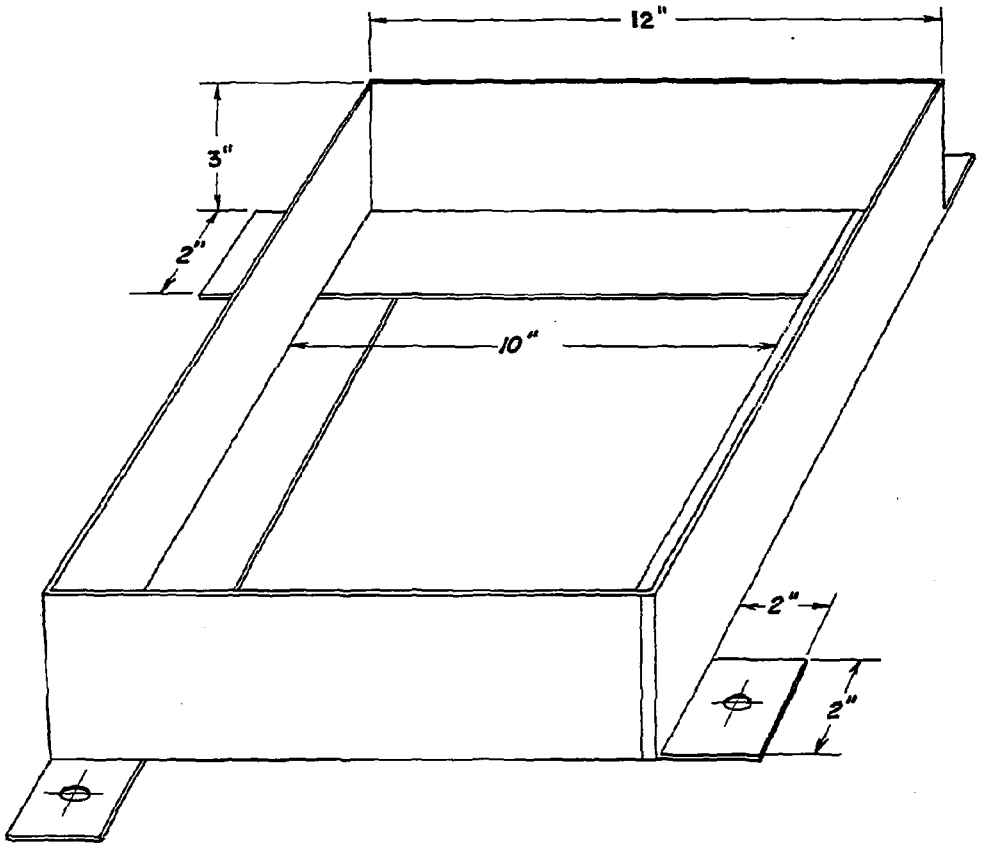
Name	*Post-shot Location*
C. E. Adams	Eniwetok
N. R. Wallace	Eniwetok
A. R. Worley, LT, USN	Parry

The laboratory work was done by the following men:

1. Sedimentation fractionation and radioautographic procedures: C. E. Adams, J. W. Washkuhn, N. R. Wallace, J. P. Wittman, and J. V. Zaccor.
2. Radiochemical analyses: M. H. Rowell, E. M. Scadden, J. C. Sheppard, and W. H. Shipman.
3. Spectrochemical analysis: J. Pasqual and J. Spasoff.
4. X-ray diffraction analysis: T. H. Anderson.

B.2 FREIGHT MOVEMENT

To Site:	Sea freight, 109 cu ft, 0.5 ton
	Air freight, 11 cu ft, 145 lb
From Site:	Air freight, 6 cu ft, 115 lb



MATERIAL - 1/32" SOFT ALUMINUM PLATE

FIG. 2.1 Fall-out Plate Holder

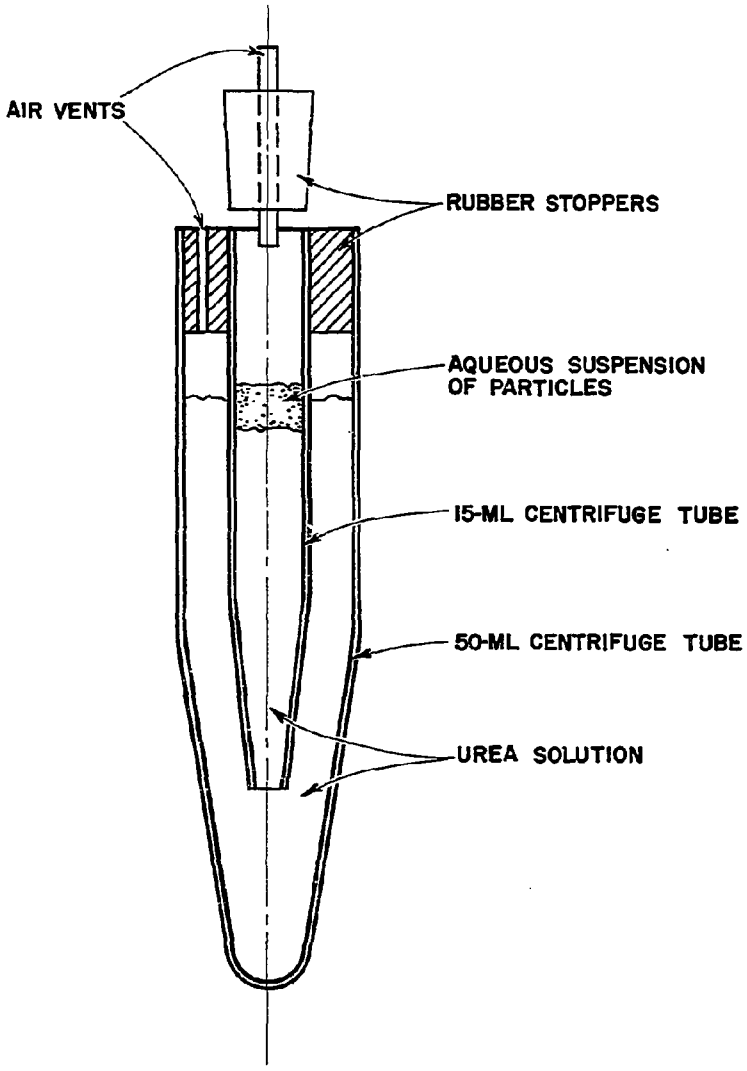


FIG. 3.1 Sedimentation Tube Assembly

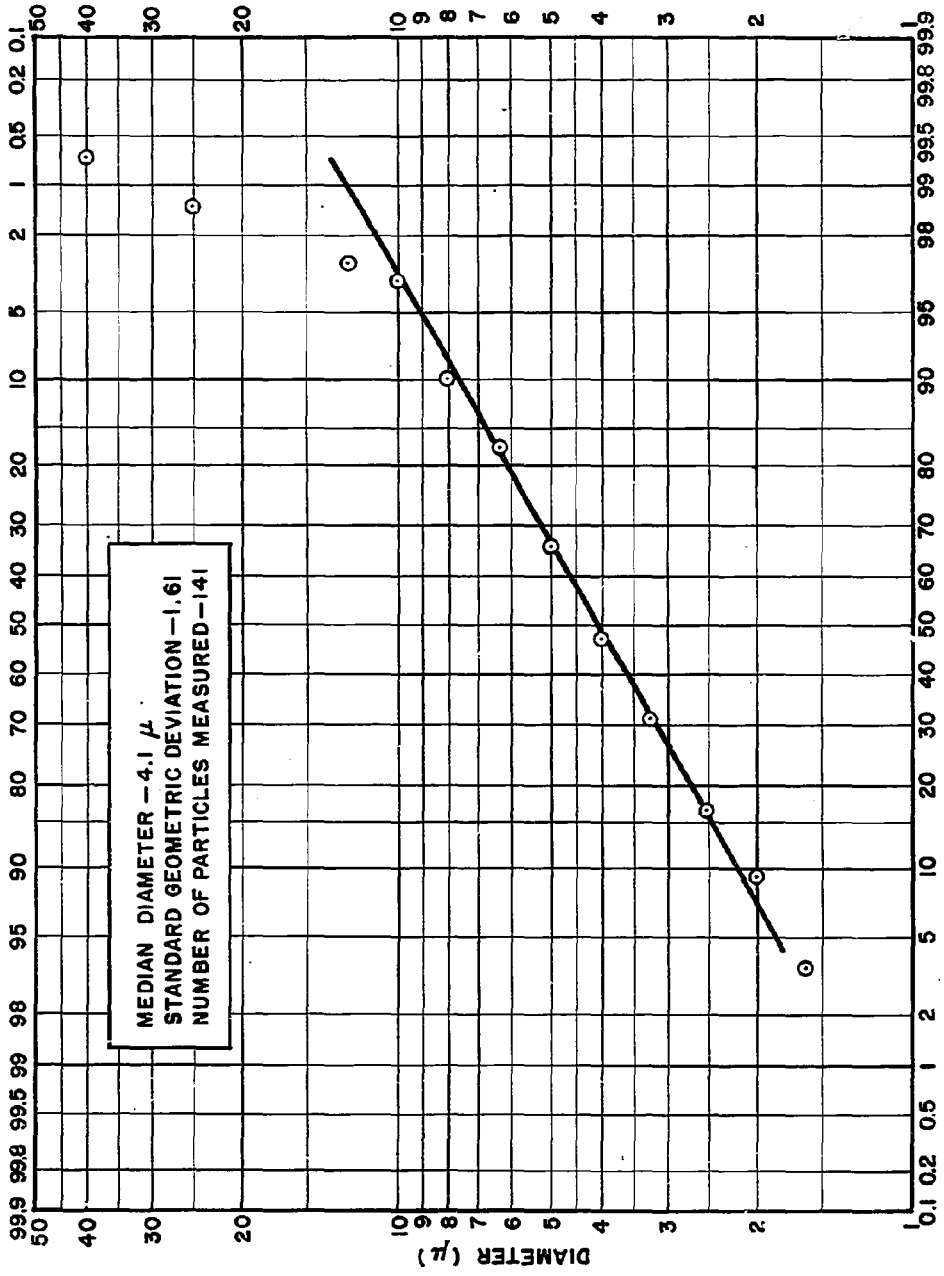


FIG. 3.2 Size Distribution of Individual Radioactive Spheres Found in Samples from Rigili Island (Dog Shot)

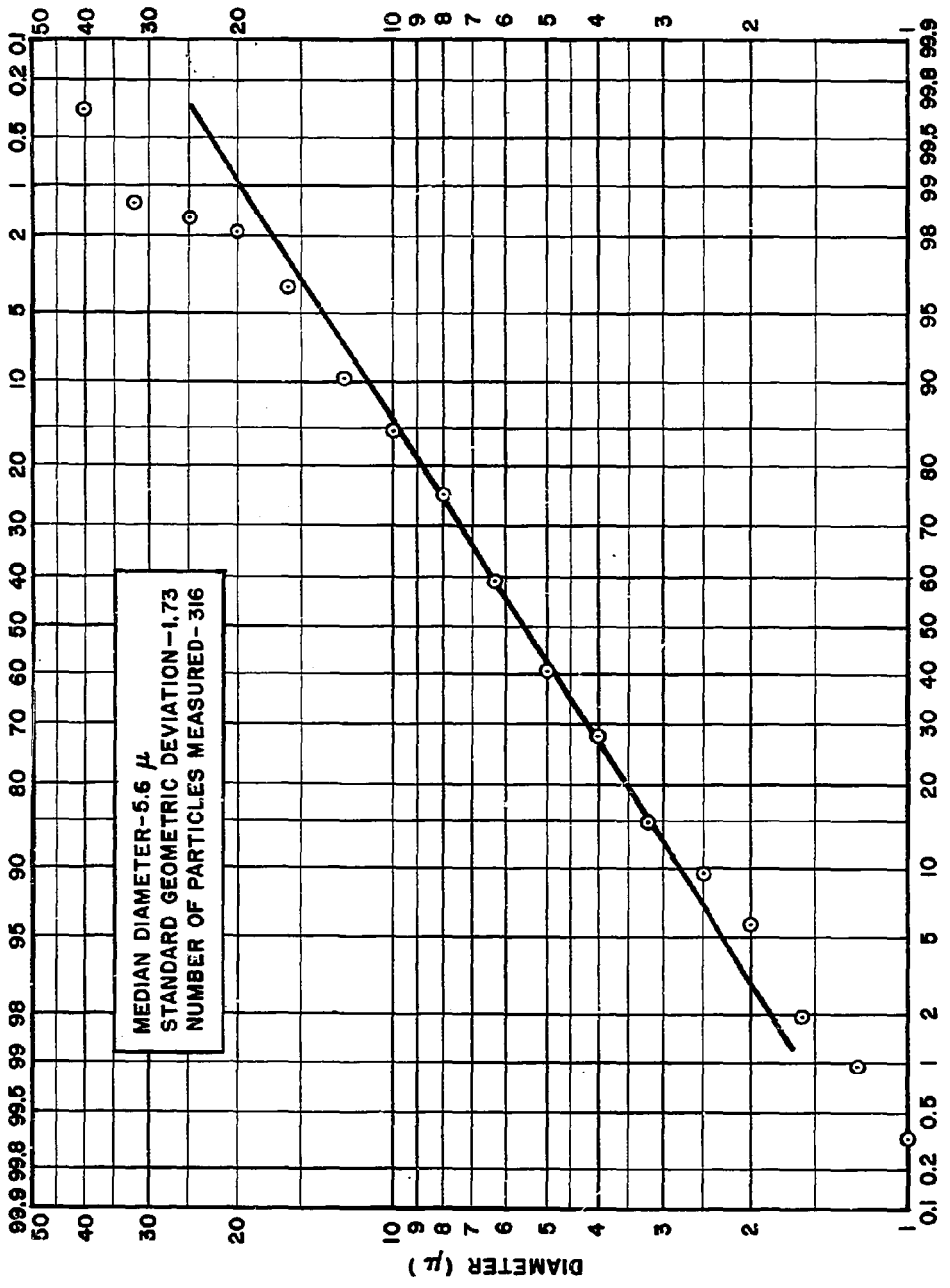


FIG. 3.3 Size Distribution of Individual Radioactive Spheres Found in Samples from Bogallua Island (Easy Shot)

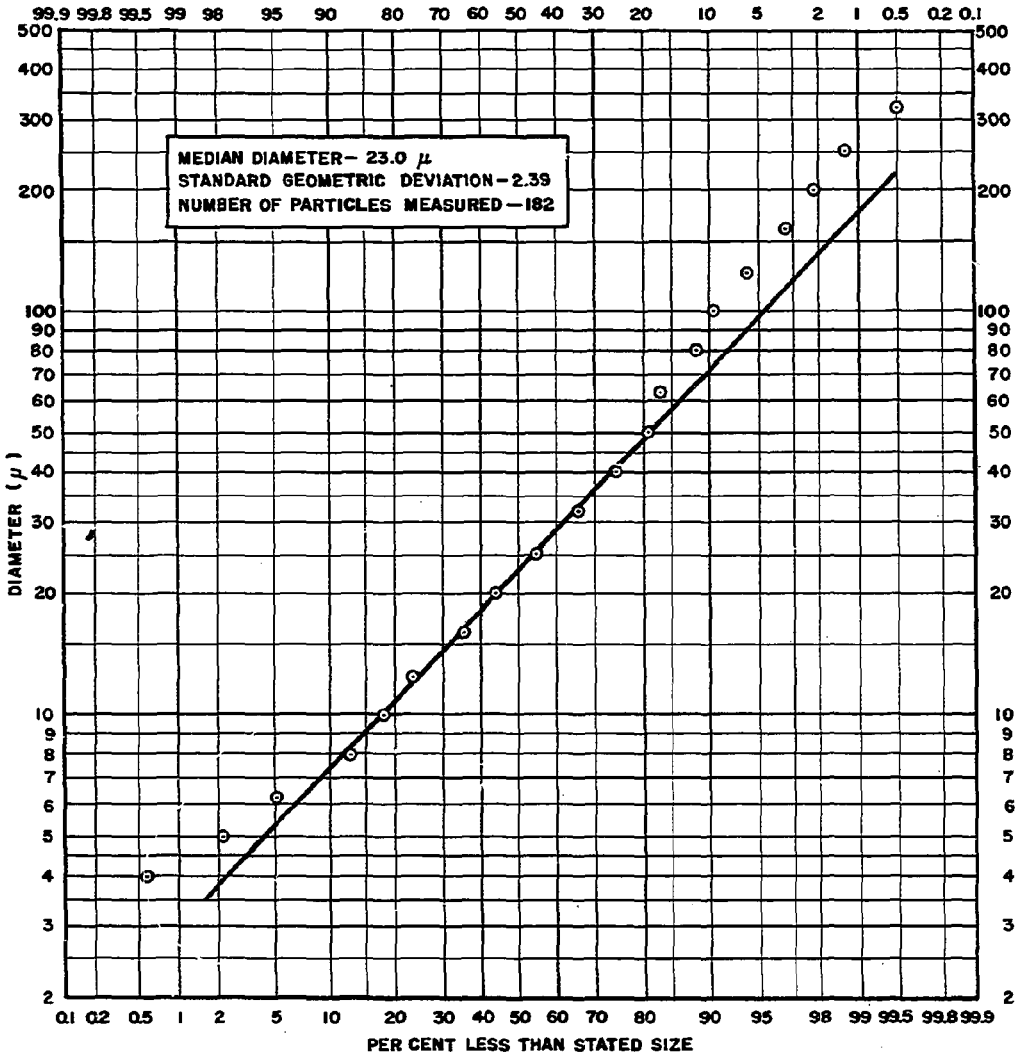


FIG. 3.4 Size Distribution of Radioactive Coral Grains Found in Samples from Rigili Island (Dog Shot)

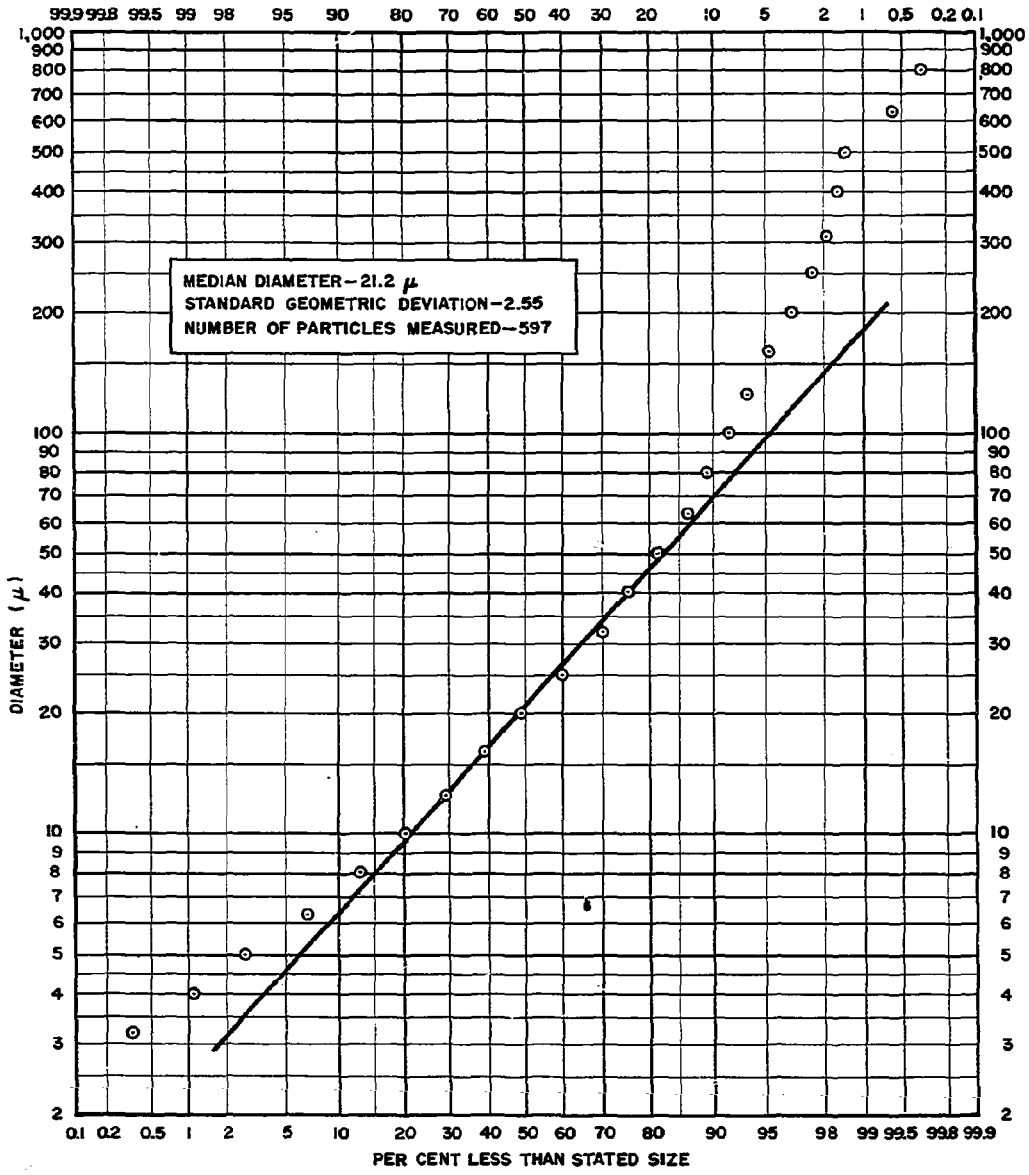


FIG. 3.5 Size Distribution of Radioactive Coral Grains Found in Samples from Bogallua Island (Easy Shot)

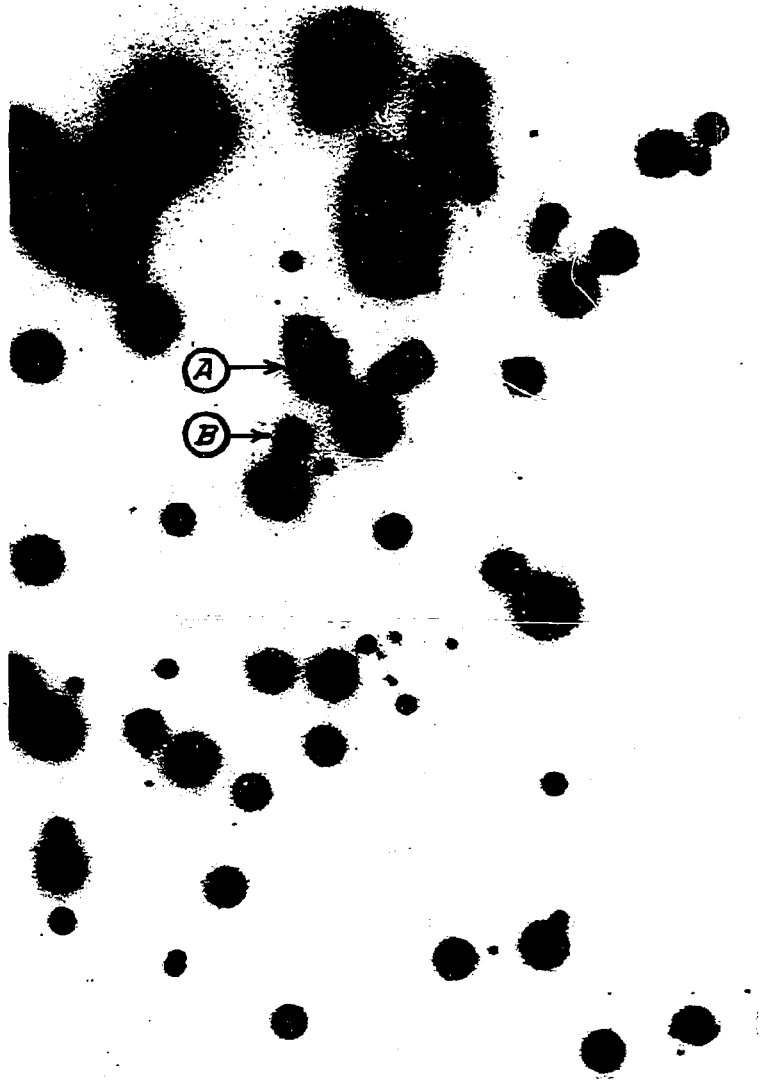


FIG. 3.6 Radioautograph of a Fall-out Plate from Parry Island (Dog Shot)

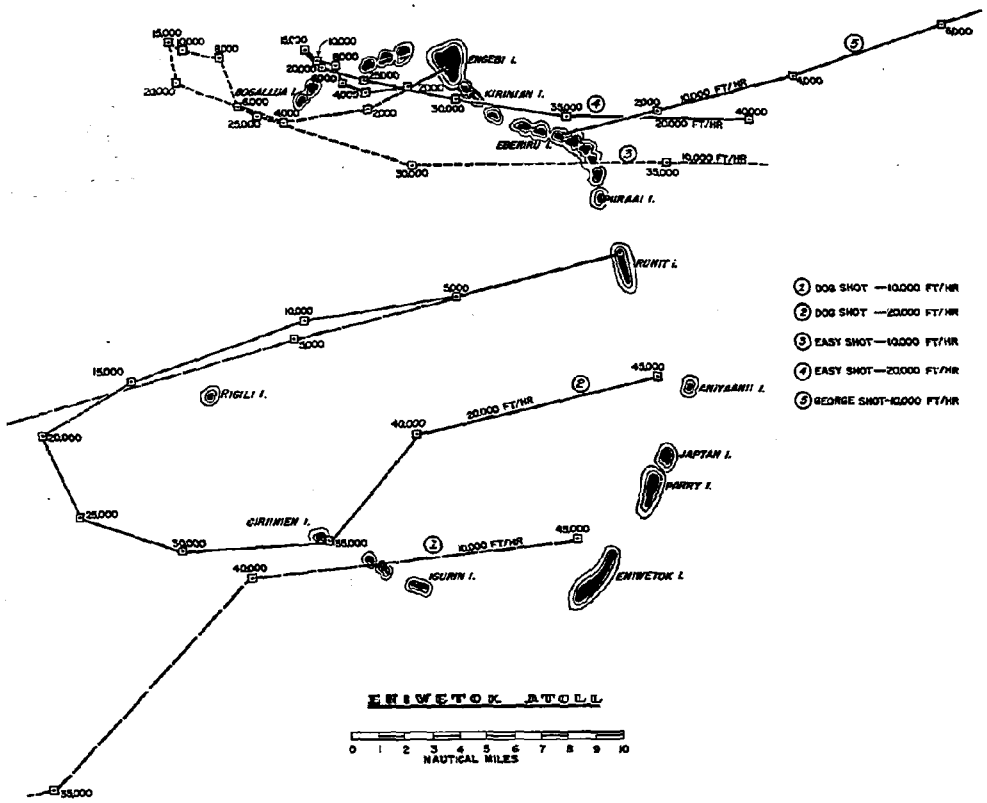


FIG. 4.1 Probable Fall-out Paths Plotted from Wind Velocity Data